Ultra-High Energy Cosmic Rays: The Annihilation of Super-Heavy Relics

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We investigate the possibility that ultra-high energy cosmic rays (UHECRs) originate from the annihilation of relic superheavy (SH) dark matter in the Galactic halo. In order to fit the data on UHECRs, a cross section of $\langle\sigma_A v\rangle \sim 10^{-26}\mathrm{cm}^2(M_X/10^{12}\,\mathrm{GeV})^{3/2}$ is required if the SH dark matter follows a Navarro–Frenk–White (NFW) density profile. This would require extremely large-l contributions to the annihilation cross section. An interesting finding of our calculation is that the annihilation in sub-galactic clumps of dark matter dominates over the annihilations in the smooth dark matter halo, thus implying much smaller values of the cross section needed to explain the observed fluxes of UHECRs.

1. Introduction

The detection of particles with energy in excess of 10^{20} eV is one of the unsolved mysteries of modern astrophysics and might represent one of the many signals of the existence of physics well beyond the standard model of particle physics. In [1,2] it was proposed the appealing possibility that this mystery might be related to another problem, the origin of dark matter. In fact the dark matter might be made of SH relics of the big bang [4–7] with lifetimes possibly exceeding the age of the universe. The rare decays of these SH particles (with masses in excess of 10^{12} GeV) naturally generates UHECRs from the top, that is as end-product of their decay. In order to saturate the dark matter content of the universe and at the same time explain the fluxes of UHECRs, the lifetime of the SH relics should be of order 10^{22} years, which is difficult to achieve for such massive particles unless some discrete conserved symmetry is introduced that prevents the natural decay of the relics on much shorter time scales.

In this paper we investigate an alternative possibility, consisting in the annihilation of SH relics rather than in their decay. The simple assumption that dark matter is a thermal relic limits the maximum mass of the dark matter particle to less than a few hundred TeV. However, it has been recently pointed out that dark particles might have never experienced local chemical equilibrium during the evolution of the universe, and that their mass may be in the range 10^{12} to 10^{19} GeV, much larger than the mass of thermal WIMPs [4–7].

In this paper we calculate the expected flux of UHECRs from the smooth dark matter content of our Galaxy, and the flux due to clumps of dark matter in the halo.

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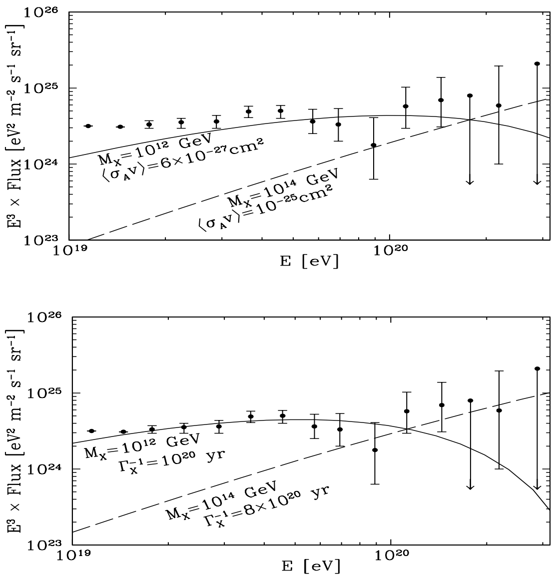

Figure 1. UHECR spectra from SH particle annihilation (upper panel) or decay (lower panel). For both figures the solid (dashed) lines are for $M_X = 10^{12}\,\text{GeV}$ ($M_X = 10^{14}\,\text{GeV}$). Cross sections and decay rates are indicated in the plot.

2. SH Dark matter annihilation and UHECRs

In calculating the UHE cosmic ray flux from a smooth SH dark matter distribution in the galactic halo, we assume a halo density spherically symmetric about the galactic center, in the form of a NFW profile [8] $n_X(d) = \frac{N_0}{d(d+d_s)^2}$. We will use $d_s = 3d_\odot = 24\,\text{kpc}$ in our numerical estimates, where $d_\odot \simeq 8\,\text{kpc}$ is the distance of the solar system from the galactic center. The dimensionless parameter N_0 may be found by requiring that the total mass of the Galaxy is $2 \times 10^{12} M_\odot$. For simplicity, we will assume that each annihilation produces two quark initiated jets, each of energy M_X, while the decay of a SH particle produces two jets, each of energy $M_X/2$. The energy spectrum of observed UHE cosmic ray events from annihilation is determined by the energy distribution of the particles in each jet, which we take to equal the fragmentation function in the modified leading logarithmic approximation (MLLA) [9], which was also employed in [1,3].

We also use the MLLA limiting spectrum in the results of Fig. 1. Calculating the resulting UHE cosmic ray flux in the annihilation model, and comparing it to the similar calculation in the decay scenario, we obtain the results shown in Fig. 1 (the data points are from AGASA). In order to provide enough events to explain the observed UHE cosmic rays, $\langle\sigma_A v\rangle$ has to be in the range $10^{-25}\,\text{cm}^2$ to $10^{-27}\,\text{cm}^2$, which is well in excess of the unitarity bound to the l-wave reaction cross section [10,13,14]. The unitarity bound essentially states that the annihilation cross section must be smaller than M_X^{-2}. However, as emphasized by Hui [14], there are several ways to evade the bound. The annihilation cross section may be larger if there are fundamental length scales in the problem larger than M_X^{-1}.

A related issue is the typical energy of the annihilation products. In this paper we assume that annihilation produces two jets, each with energy approximately M_X. It is easy to imagine that with the finite-size effects discussed above, there is the possibility that annihilation will produce many soft particles, rather than essentially two particles each of energy M_X. An example that suits our needs is the annihilation of a monopole-antimonopole pair, as discussed at length in [11]. We regard the requisite size of the annihilation cross section to be the most unattractive feature of the annihilation scenario.

This problem becomes less severe when the clumped component of the dark matter distribution in the Galactic halo is taken into account. The spatial and mass distribution of the clumps is taken from numerical N-body simulations (see [11] and [12]). The presence of cuspy density profiles in the clumps makes their contribution to the diffuse flux of UHECRs dominant over the NFW smooth component. The ratio of the clumped to smooth contributions for isothermal and NFW profiles for the clumps and for different values of M_X is plotted in Fig. 2. In the case of isothermal clumps, where the density profile of a single clump scales like $1/r^2$, the main contribution to

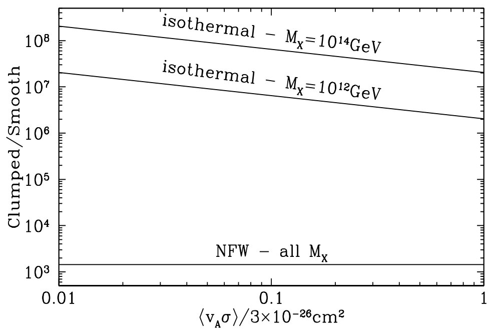

Figure 2. The ratio of events from the subclump component to the smooth component assuming either an isothermal or a NFW profile for the subclumps.

the annihilation comes from the inner regions of the clumps, so that it is crucial to define a minimum radius R_{min}, determined by the annihilation efficiency. In [11] it is explained in detail the effect of two different definitions for R_{min}.

Another peculiar prediction of the annihilation of SH relics in clumps of dark matter in the halo consists of a peculiar pattern of small scale anisotropies. Several multiple events within degree scales would be observed if annihilation in the clumps generates the UHECRs. A detailed simulation was carried out in [11]. The model also predicts a large scale anisotropy in the direction of the galactic center, which is an important test to be carried out by the future experiments, that will be able to see the direction of the galactic center.

3. Conclusions

Our calculations can be summarized in the following points: 1) the annihilation scenario for the origin of UHECRs requires cross sections that may be larger that the unitarity bound. Although not a killing factor, for the reasons explained above, this is certainly an unappealing feature of the model; 2) the annihilations in clumps of galactic dark matter dominate over the contribution of a smooth NFW dark matter profile, requiring correspondingly smaller values for the annihilation cross section; 3) the pattern of anisotropies is such that both a large scale (dipole) anisotropy and a degree scale anisotropy is to be expected if UHECRs are generated in the annihilations of SH relics in galactic SH dark matter.

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